The Highly Eccentric Pre−Main Sequence Spectroscopic Binary RX J0529.3+1210

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ABSTRACT

The young system RX J0529.3+1210 was initially identified as a single−lined spectroscopic binary. Using high−resolution infrared spectra, acquired with NIRSPEC on Keck II, we measured radial velocities for the secondary. The method of using the infrared regime to convert single−lined spectra into double−lined spectra, and derive the mass ratio for the binary system, has been successfully used for a number of young, low-mass binaries. For RX J0529.3+1210, a long-period (462 days) and highly eccentric (0.88) binary system, we determine the mass ratio to be 0.78 ± 0.05 using the infrared double-lined velocity data alone, and 0.73 ± 0.23 combining visible light and infrared data in a full orbital solution. The large uncertainty in the latter is the result of the sparse sampling in the infrared and the high eccentricity: the stars do not have a large velocity separation during most of their ∼1.3 year orbit. A mass ratio close to unity, consistent with the high end of the 1σ uncertainty for this mass ratio value, is inconsistent with the lack of a visible light detection of the secondary component. We outline several scenarios for a color difference in the two stars, such as one heavily spotted component, higher order multiplicity, or a unique evolutionary stage, favoring detection of only the primary star in visible light, even in a mass ratio ∼1 system. However, the evidence points to a lower ratio. Although RX J0529.3+1210 exhibits no excess at near-infrared wavelengths, a small 24 μm excess is detected, consistent with circumbinary dust. The properties of this binary and its membership in λ Ori versus a new nearby stellar moving group at ∼90 pc are discussed. We speculate on the origin of this unusual system and on the impact of such high eccentricity, the largest observed in a pre−main sequence double−lined system to date, on the potential for planet formation.

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Subject headings: Stars: Binaries: Spectroscopic, Stars: Evolution, Stars: Pre-Main-Sequence

1. Introduction

Understanding the process of star formation requires reliable observations of fundamental stellar properties so that theoretical models can be tested. The copious population of young binary systems, however, complicates the problem. The binary fraction can be high (Mathieu et al. 2000), and may depend on the density of the star forming region (Beck et al. 2003) and spectral type of the primary (Lada 2006), underscoring the importance of their study. Fortuitously, binary stars serve two purposes. One, characterization of their frequency, separation distribution, and mass ratio distribution for a given star forming region (SFR) provides clues to the broad star forming properties (angular momentum, density, turbulence, etc.) of the parent molecular cloud. Two, the special class of very small separation spectroscopic binaries with periods sufficiently short to enable the measurement of the individual stellar velocities, and thus the system's mass ratio, are potential targets for the dynamical determination of individual component stellar masses (e.g., Steffen et al. 2001; Prato et al. 2002a; Boden et al. 2005; Stassun et al. 2007). Knowledge of absolute masses and observable properties, such as effective temperature and luminosity, plays a key role in the improvement of pre-main sequence (PMS) evolutionary models (Palla & Stahler 2001).

Once spectroscopic binaries have been identified, it is necessary to characterize their properties. It is often the case with low mass-ratio systems that they are identified as single−lined spectroscopic binaries when observed in visible light (Mazeh et al. 2002), in which case the large difference in flux between the primary and secondary at short wavelengths prevents detection of the secondary component and thus the measurement of the mass ratio for the system. In the Raleigh-Jeans regime, however, flux scales much less steeply as a function of mass. Thus, by observing single-lined spectroscopic binaries with infrared (IR) spectroscopy we are able to improve our chances of detecting the lower-mass secondary not seen in visible light. This technique was initially outlined in Prato et al. (2002b) and Mazeh et al. (2002, 2003). Our primary motivation for observing RX J0529.3+1210 was to use this IR approach to determine the mass ratio of the system by converting it into a double-lined spectroscopic binary. Given that the secondary had not been detected in visible light, we anticipated a relatively low mass ratio for RX J0529.3+1210.

With the advent of the *Röntgensatellit (ROSAT)* all-sky survey, a number of researchers

began a search for X-ray sources with optical counterparts of brightness consistent with membership in nearby SFRs, motivated in part by the goal of detecting the "post-T Tauri" population postulated by Herbig (1978). In follow up observations of X-ray sources near Taurus, RX J0529.3+1210 was identified variously as a PMS star (Neuhauser et al. 1997; Magazzù et al. 1997) and a post-T Tauri star (Magazzù et al. 1999); high-resolution visible light spectroscopy revealed its spectroscopic binary nature (Neuhauser et al. 1997). Torres et al. (2002) undertook a seven year campaign to characterize the orbits of all spectroscopic binaries identified in the X-ray sample of Neuhauser et al. (1995) and Neuhauser et al. (1997), including RX J0529.3+1210. Table 1 summarizes the general properties of this system. The ∼3 dozen high-resolution visible light spectra taken of this binary suggested the presence of a secondary star; however, a conclusive identification was not possible. A single-lined orbital solution was determined, although, probably owing to the extremely high eccentricity of the system the uncertainties are relatively large.

This paper describes the results of using high resolution IR spectroscopy to observe RX J0529.3+1210 and determine the component radial velocities. RX J0529.3+1210 is the most eccentric pre−main sequence spectroscopic binary known to date. This provides a unique context in which to speculate on the formation of the system and on the impact of the stellar dynamics on potential planet formation. In §2 we briefly describe our observations and data reduction. Our analysis and results appear in §3. Section 4 provides a discussion, and §5 summarizes our findings.

2. Observations and Data Reduction

Our observations were made during six epochs between 2002 January and 2004 December with the Keck II 10-m telescope on Mauna Kea. The UT dates of observation are listed in Table 2. H-band data, at a central wavelength of $\sim$1.555 μm, were obtained using the facility near-infrared, cross-dispersed, cryogenic spectrograph NIRSPEC (McLean et al. 1998; 2000). NIRSPEC employs a 1024 × 1024 ALADDIN InSb array detector. We used the $0.288''$ (2 pixel) × $24''$ slit, yielding an OH night sky emission line determined resolution of R=25,000. Source acquisition was accomplished with the slit viewing camera, SCAM, which utilizes a 256 × 256 HgCdTe detector with $0.18''$ pixels. RX J0529.3+1210 has a 2MASS H-band magnitude of 9.40; integration times for individual frames were between 60 and 240 s. We nodded the telescope $10''$ between two positions on the slit to allow for background subtraction between sequential spectra.

All spectroscopic reductions were made with the REDSPEC package, software written

at UCLA by S. Kim, L. Prato, and I. McLean specifically for the analysis of NIRSPEC data[1], following the procedures outlined by Prato et al. (2002a). We used the central order, 49, which covers 1.545 to 1.567 μm at our setting; this order has three advantages. One, it is rich in both atomic and molecular lines and is therefore suitable for identifying spectra of both warm and cool stars. Two, the OH night sky emission lines across order 49 are numerous and well-distributed, yielding accurate and precise dispersion solutions. Three, this order has the advantage of lacking prominent telluric absorption lines. Consequently, we did not have to divide by telluric standard star spectra.

On UT dates 2004 December 24 and 2008 January 17 images were taken of RX J0529.3+1210, point spread function (PSF) stars, and photometric standards at the Keck II telescope with the NIRC2 camera behind the adaptive optics (AO) system (Wizinowich et al. 2000). The plate scale was 0.01″ per pixel and integration times were 0.18 s for the L' filter, 0.20 s for the K' filter, and 1.0 s for the narrow K-continuum filter. Ten coadds were made per image, and two images were obtained at each location in a five-point box dither pattern. Seeing conditions were excellent for both nights. With the use of customized IDL reduction and analysis routines, images were flat-fielded, cleaned of bad pixels, and compared with PSF stars to search for higher order multiplicity and evidence for extended sources. L' and K-continuum filter data from 2008 January 17 (UT) were reduced with standard photometric techniques, including flat-fielding, background subtraction, aperture photometry, and airmass correction.

3. Analysis and Results

The spectra from the six epochs of observation are shown in Figure 1. Individual stellar radial velocities were measured by using two-dimensional cross correlation (e. g., Zucker & Mazeh 1994); observed or synthetic spectral templates were shifted in relative velocity to maximize the correlation with the observed binary spectrum, thus identifying the component radial velocities. The observed template spectra (Prato et al. 2002a) that best matched our data were BS 8086 and GL 436, spectral types K7 and M2.5, consistent with Torres et al. (2002). The corresponding best rotational velocities were 20 km s^{-1} for the primary and 25 km s^{-1} for the secondary. Flux ratios determined by cross-correlation range from 0.50 to 0.69 and have an average value of ∼0.6.

Schaefer et al. (2008) employ synthetic spectra in their final radial velocity analysis of the components of the young spectroscopic binary, Haro 1-14c. In addition to using observed templates, we also fit the components of RX J0529.3+1210 with synthetic template spectra,

[1]See: http://www2.keck.hawaii.edu/inst/nirspec/redspec/index.html

calculated from the updated NextGen models (Hauschildt et al. 1999). This is desirable because observed template spectra have inherent radial velocity uncertainties, whereas the synthetic template spectra have no associated velocity measurement uncertainties. Thus, by using synthetic templates, the uncertainties in the component radial velocities of a spectroscopic binary are likely attributable to factors such as the signal to noise ratio of the observed spectroscopic binary spectra and imperfect matches to model stellar atmosphere spectra. For RX J0529.3+1210 we were unable to determine consistent velocity solutions using synthetic templates for both the primary and secondary stars because of the poor fit of a synthetic secondary to the observed spectra. However, the combination of a synthetic spectrum for the primary component (rotated to 30 km s^{-1}) and the GL 436 observed template for the secondary (rotated to 25−30 km s^{-1}) was successful. The velocities derived from this approach appear in Table 2, columns (3) and (4). The velocity uncertainties associated with the primary star are 0.5 km s^{-1} and with the secondary star are 2.0 km s^{-1}. Analysis of the spectra with only the observed templates yields results that are consistent to within 1σ with the mixed approach presented here.

Following Wilson (1941), we plot the six epochs of the primary versus secondary radial velocities (Figure 2), extracted from our IR spectra, and derive a mass ratio of q=0.78±0.05 and a center-of-mass velocity of $\gamma = +19.01 \pm 0.87$ km s^{-1}. We combined our radial velocities for the primary and secondary stars with the 34 measurements for the primary star presented in Torres et al. (2002) and solved for the best-fit orbital elements in the χ^2 sense. The orbital fit is a standard least-squares program using the Levenberg-Marquardt method taken from Press et al. (1992). Initial guesses for the solution are found by using an amoeba search routine also from Press et al. (1992). The orbital elements are given in Table 3. The mass ratio and the center-of-mass velocity found from the single- and double-lined velocities together are consistent with those derived from Figure 2 to within 1σ, although the mass ratio calculated from the full orbital solution, 0.73±0.23, has a large associated uncertainty. Because the primary star velocity measurements dominate the data set, the orbital parameters are similar to those found in Torres et al. (2002). Determination of the orbital solution from only the double-lined velocities yields results consistent with the combined single- and double-lined solution but with much larger uncertainties. We describe future work to improve our orbital fit in §4.4.

Figure 3 shows the primary star velocities from Torres et al. (2002) along with IR determined radial velocities for both the primary and secondary stars plotted as a function of phase. The phases for the IR observations were computed by taking the difference in the heliocentric Julian Day (HJD) from the last observation made by Torres et al. (2002) and the HJDs of our observations and dividing by our period (Table 3). The errors associated with the velocities are typically a few km s^{-1} for the Torres et al. (2002) data, 0.5 km s^{-1}

for our primary star data, and 2.0 km s^{-1} for our secondary data. Our orbital solution is also plotted. Clearly there is scatter of up to several sigma in many of the data points, particularly among the visible light data with velocities closer to the center-of-mass velocity of the system, compared to the orbital solution. Torres et al. (2002) give a typical radial velocity uncertainty for all their targets of 0.5 km s^{-1}, probably an underestimate in the case of RX J0529.3+1210. The IR data are within 1−2 σ of the orbital solution. The sample of PMS spectroscopic binary star eccentricities as a function of period, based on data from Melo et al. (2001), is plotted in Figure 4 and indicates that RX J0529.3+1210 is the most eccentric PMS spectroscopic binary known to date. The combination of the system orientation and high eccentricity results in fairly low velocity amplitudes during the majority of the orbital period. Until the high-velocity cusp of the radial velocity versus phase curve is well-sampled, the uncertainty in the elements of this system will remain large.

Near-IR J−H and H−K colors for RX J0529.3+1210 were calculated from 2MASS JHK magnitudes and plotted on a color-color diagram. The location in the color-color plane of this source is consistent with that of a late K or early M dwarf. There is no near-IR excess evident. From our Keck+NIRC2 data we determine a K-continuum magnitude of 9.23±0.27, consistent with 2MASS measurements (Table 1), and an L'-band magnitude of 9.05±0.11 from our 2008 Keck AO images. The resultant K−L' color is thus 0.18±0.29 magnitudes.

In the AO images from 2008 January 17, RX J0529.3+1210 appears to be extended in comparison with the observed single star PSFs. Modeling RX J0529.3+1210 as a binary with the single star DN Tau used as a PSF yields a separation of $0.018'' \pm 0.006''$ at a position angle of $223^\circ \pm 18^\circ$ and a secondary-to-primary K-band flux ratio of 0.66 ± 0.18. The reliability of the solution is likely to be low because of the difficulty in measuring separations this far below the diffraction limit. We also note the possibility that RX J0529.3+1210 could be broadened by a lower AO correction rate during the observations as compared with that of the single star. However, the consistency of the flux ratio with the H-band spectroscopic values determined by cross-correlation provides support that we are seeing evidence of the companion in RX J0529.3+1210. We do not see any extension in the 2004 December 24 images of RX J0529.3+1210, which is consistent with the binary being near periastron, whereas in 2008 January the companion was approaching apastron.

4. Discussion

4.1. Where and How Old is RX J0529.3+1210?

The projected location of RX J0529.3+1210 is associated with a high-density area in the CO maps of Dolan & Mathieu (2001) for the λ Ori region. However, Dolan & Mathieu (2001) find a mean radial velocity for the strong lithium sources identified in λ Ori of 24.5 km s^{-1}, with a dispersion of only 2.3 km s^{-1}. Our center-of-mass velocity for RX J0529.3+1210 is 18.38 km s$^{-1} \pm 0.30$, indistinguishable from that found by Torres et al. (2002). Thus, on the basis of radial velocities alone, it seems unlikely that the system is associated with λ Ori since RX J0529.3+1210's center-of-mass velocity is inconsistent with that of λ Ori at the 3σ level.

Using the 2MASS JHK magnitudes of RX J0529.3+1210, an effective temperature (T_{eff}) for a K7/M0 of 3900 K (Luhman et al. 2003; Broeg et al. 2006), and the nominal distance to λ Ori (400 pc; Barrado y Navascués 2005) we have estimated the luminosity and placed the system on an H-R diagram. We find L = 3.44 $\pm$ 0.01 $L_{\odot}$, yielding an age of $\sim$0.1 Myr using the PMS tracks of Palla & Stahler (1999). Accounting for a companion star with luminosity equal to that of the primary results in an age of $\sim$0.5 Myr. Using the tracks of Baraffe et al. (1998), or absolute K magnitude and the tracks of Siess et al. (2000), we obtain similar age estimates.

Barrado y Navascués (2005) estimates the age of λ Ori to be between 3 and 10 Myr, Barrado y Navascués et al. (2007) find an age of 5 Myr, and Dolan & Mathieu (2001) describe a spread in ages from 1 to 10 Myr. A <<1 Myr object is expected to be at least somewhat embedded in its natal cloud and associated with circumstellar material, yet near-IR colors from 2MASS magnitudes indicate zero extinction, no veiling is detected in the spectra, and the Hα emission line equivalent width (Table 1) is only 2Å. We consider two possible mechanisms for disk dissipation in this system, photoevaporation from nearby hot stars and the orbital dynamics of RX J0529.3+1210 itself.

The projected separation of the B8 star HD 36104 (Dolan & Mathieu 2001) from RX J0529.3+1210 is $\sim$1 pc if both are assumed to be at a distance of 400 pc. Dolan & Mathieu (2001) discuss the surprising lack of evidence for accretion disks around the PMS stars in the central λ Ori cluster and suggest that photoevaporation and/or possibly a supernova event 1$-$2 Myr ago played a role in the dispersion of disks in the local young low-mass stellar population. RX J0529.3+1210, located just north of the central cluster in the Barnard 30 dark cloud, could have experienced photoevaporation from the nearby B star at a young age, obliterating circumstellar material, although this is probably unlikely given the long survival time of proplyds in the Trapezium (O'Dell 1998).

Given the extremely high eccentricity of this binary, however, the action of the companion star may have precluded formation of, or dissipated any, circumstellar material. With an assumed primary star mass of 0.75 $M_\odot$ and the mass function from Torres et al. (2002), we find a minimum secondary star mass of 0.40 $M_\odot$, and thus a minimum total mass of 1.15 $M_\odot$. In conjunction with the 461.89 day period, this yields a periastron separation of 0.15 AU and an apastron separation of 2.30 AU. It is unknown if orbital evolution may have occurred, or even whether it is possible that this unusual system formed by capture, but if RX J0529.3+1210 is located in λ Ori with an age of <1 Myr, then it seems likely that the system formed in a similar configuration to its present one.

Independent of the potentially harsh λ Ori environment and the orbital dynamics of RX J0529.3+1210, the system manifests spectra of similar surface gravity to dwarf stars, as well as a relatively small lithium equivalent width, in comparison to classical T Tauri stars (Strom et al. 1989; Stahler & Palla 2005). The lithium and Hα equivalent widths of Dolan & Mathieu (2001) for λ Ori average greater than twice what is found for RX J0529.3+1210 and are consistent with the classical and weak-lined T-Tauri limits defined by Martín (1998). According to these limits, RX J0529.3+1210 would be a post-T Tauri star and have one of the lowest lithium and Hα equivalent widths in the λ Ori region. These characteristics are inconsistent with an age of <1 Myr.

Alternatively, RX J0529.3+1210 could be an older, closer object. Mamajek (2007) describes a new candidate moving group, 32 Ori, consisting of a small cluster of X-ray bright, late type stars. The ∼10 young stars identified in the group are located around 5^h 20^m to 5^h 30^m and +6 deg, at the proposed distance of ∼90 pc. RX J0529.3+1210 is about 9 pc from the central clump of objects in 32 Ori and is one of the members used by Mamajek to define the common proper motion group (E. Mamajek 2008, private communication). Given the proper motion of RX J0529.3+1210, pmRA = 4.1 ± 5.8 mas/yr and pmDec = −30.7 ± 5.8 mas/yr, compared to the proper motions of the stars λ Ori (pmRA = 0.8 ± 1.5, pmDec = −2.3 ± 1.5) and 32 Ori (pmRA = 6.57 ± 1.15, pmDec = −32.45 ± 0.48), evidence in support of membership in the 32 Ori group is compelling (Perryman et al. 1997; Zacharias et al. 2004).

Again combining the 2MASS JHK magnitudes of RX J0529.3+1210, an effective temperature of 3900 K, and a distance now of 90 pc, we find $L = 0.17 \pm 0.02\ L_\odot$, giving an age for RX J0529.3+1210 on the tracks of Palla & Stahler (1999) of ∼15±5 Myr, consistent with the 25±10 Myr age derived by Mamajek (2007) for the candidate group members. Mamajek (2007) lists a group radial velocity of 18 km s^{-1}, in excellent agreement with our measured center-of-mass velocity (Table 2).

Morales Calderon (2008, in prep) has observed the λ Ori region with the *Spitzer* space

telescope and finds a 3 σ detection of RX J0529.3+1210 at 24 μm with a 20 % excess above a 3900 K photosphere. For a star with L=0.17 $L_{\odot}$, the equilibrium temperature of a black-body grain with peak emission at 24 μm corresponds to a distance of 4.36 AU. A more realistic treatment of the dust grain distribution would necessarily take into account the additional flux from the secondary star, yielding a larger distance from the center-of-mass of the system to the putative dust. However, given the estimated apastron separation of 2.30 AU, a lower limit of 4.36 AU for the dust radius from the system center illustrates the plausibility of a circumbinary debris disk. Additional *Spitzer* observations at shorter wavelengths have been taken and should reveal more information regarding the extent and location of the dust (Mamajek 2008, in preparation).

The lack of J−H, H−K, and K−L excesses is hardly surprising. For black-body grains with a peak wavelength in the L band, the corresponding disk temperature occurs at a distance of ∼0.1 AU, nearly coincident with the binary periastron. Stable dust in this system is most likely to be located in a circumbinary distribution. Furthermore, if the closer distance and therefore older age for this system implied by membership in 32 Ori are correct, then the presence of an evolved debris disk would not be unusual (e.g., Trilling et al. 2008).

Finally, the fact that the RX J0529.3+1210 secondary was possibly detected in our AO images strongly supports the ∼90 pc distance. For the projected separation of 0.018”, determined using PSF fitting, and a distance of 90 pc, the corresponding distance in AU is 1.6±0.54, not too different from our estimated apastron of 2.30 AU. For a distance of 400 pc the separation would be 7.2±2.4 AU. Based on the currently available data, it therefore appears that RX J0529.3+1210 is associated with the new 32 Ori group, not with λ Ori, and has an age of ∼15 Myr.

4.2. The Mass and Flux Ratios of RX J0529.3+1210

Torres et al. (2002) note that the appearance of the velocity correlation function for RX J0529.3+1210 suggests the presence of at least one other star in the system. For a primary star mass of 0.75 $M_{\odot}$, the mass function implies a minimum secondary star mass of 0.40 $M_{\odot}$ and a minimum mass ratio of 0.53, consistent to within 1σ of the mass ratio found from the full orbital solution for the system, 0.73±0.23. The approximate H-band flux ratio measured from the cross-correlation is 0.6±0.1. The K-band flux ratio found in the best PSF fit to the January, 2008 AO images is 0.66±0.18. For a M2.5 + K7 pair, the spectral types which provided the best correlation (§3), models of Palla & Stahler (1999) and Baraffe et al. (1998) imply an H-band flux ratio of 0.4±0.1 based on components with a primary T_{eff} =3900 K and a secondary T_{eff} =3400 K (Luhman et al. 2003; Johnson

1966). Taken together, these properties suggest a relatively red color for the secondary star, hindering detection in visible light.

The IR primary and secondary velocities, presented in the Wilson plot (Figure 2), imply a range of mass ratios, from 0.73−0.83, well within the range we obtain by combining the IR and visible light data in a full orbital solution, ∼0.50−0.93. Because the full solution includes phase information, it is generally more reliable, although for RX J0529.3+1210 the sparse phase coverage during the epochs of largest velocity separation yields large uncertainties in the orbital solution. Clearly more data are merited. For the case of a mass ratio relatively close to unity in this system (i.e. 0.8−1.0), it is necessary to explain the lack of a visible light detection of the secondary star. In the following paragraphs we outline several scenarios that would account for this.

A relatively red secondary and yet a mass ratio close to unity is possible if a third component is present, as first suggested by Torres et al. (2002). If the secondary star is actually a binary pair, with a very small separation and similar component masses, then the spectral types could be consistent with the best-fitting TODCOR templates. This inner binary pair would necessarily be in an orbit in a plane relatively perpendicular to our line of sight, such that the large velocity changes would not be obvious. This scenario would imply a near-unity mass ratio yet a smaller near-IR flux ratio, and a red enough secondary system to evade visible light detection. The drawback is that it requires a very specific geometry. Such a companion might also account for the 24 μm excess.

A heavily spotted secondary star could mimic a lower temperature source, resulting in a best fitting secondary M2.5 template, a mass ratio close to 1.0, and a flux ratio <1 in the near-IR. Again, the reddening effect of the cooler temperature in the spot covered areas would increase the difficulty of visible light detection. For two T_{eff} =3900 K stars, if one has 50% of its surface covered with a 2900 K spot (Bouvier & Bertout 1989), the secondary/primary bolometric flux ratio would be ∼0.7.

For objects with ages between 10 and 30 Myr, some models (Baraffe et al. 1998; Palla & Stahler 1999) of PMS evolution indicate that targets in the mass range of the RX J0529.3+1210 primary star, 0.6−0.8 $M_{\odot}$, are located near the transition between the convective Hyashi track and the radiative Henyey track. As a result, models show a sharp turn in the mass tracks towards higher temperatures. A similar but slightly lower mass secondary star that has not yet turned this corner off of the Hyashi track, and indeed, objects with masses lower than ∼0.5 $M_{\odot}$ never will, may have a similar mass as the primary star but a much lower temperature.

These models for the system behavior are highly speculative. The absence of an unam-

biguous secondary star detection in visible light suggests that the mass ratio is *not* close to unity. A value in the 0.7 to 0.8 range is most likely based on data to date.

4.3. Binary Formation Scenarios and the Potential for Planets

The formation of such a highly eccentric multiple is challenging to understand as a primordial event given current theories of star formation (Stahler & Palla 2005). Figure 4 shows that pre−main sequence spectroscopic binaries are observed over a wide range of eccentricities. Although RX J0529.3+1210 represents the maximum of that range, it does not stand out particularly from the eccentricity distribution. Thus, some form of dynamical evolution may have taken place in this system, but, if so, it is not distinguished by an outlying eccentricity. Possibilities for dynamical evolution range from an improbable capture event to disk excitation of stellar eccentricity (Mathieu 1992). If indeed this system is >10 Myr old, only fossil evidence, such as the detected 24 μm excess, might remain of the primordial, presumably massive disk(s) responsible. In a variation of the interactions proposed by Reipurth (2000), a three body dynamical encounter between an object from outside of the binary and a companion short period binary could have stimulated the eccentricity of the system and tightened the orbit of a close (secondary) pair (§4.2). The eventual formation of a circumbinary (or circumtriple) debris disk could have been stimulated by dynamical disruption of the disks in the system in any one of these scenarios.

The formation of planets in binary systems has been observationally supported in recent years and is of primary significance since a majority of stars have companions (Eggenberger & Udry 2007). Cuntz et al. (2007) have determined the strict criteria for classifying stable and unstable planetary orbits in binary systems, however, their analysis is restricted to circular orbits. Many of the extra-solar planets observed in binaries are in wide separation systems, where the mass ratio for the stellar components is near unity and the eccentricity of the system is low. Quintana et al. (2007) have modeled the formation of terrestrial planets around individual stars in binaries and find that, for periastron distances of <5 AU, such planet formation is restricted. Considering that the periastron distance in the RX J0529.3+1210 system is only 0.15 AU, we conclude that the probability of even a low-mass circumstellar planet in RX J0529.3+1210 is remote. The trend determined by Quintana & Lissauer (2006) towards the formation of fewer circumbinary terrestrial planets in systems with apastron distances of >0.2 AU and non-zero eccentricities also bodes for poor circumbinary planetary stability around the stars in RX J0529.3+1210.

4.4. Improving our Understanding of the RX J0529.3+1210 System: Future Work

Clearly it is imperative to improve the orbital solution for RX J0529.3+1210, particularly the measurement of the mass ratio. Visible light and especially infrared data are critical to obtain, preferably at high precisions. RX J0529.3+1210 passes through its next maximum velocity separation in late December, 2009. Densely sampled high signal-to-noise spectra taken during these epochs will yield a greatly improved precision for the orbital solution.

If RX J0529.3+1210 is located at a distance of only 90 pc, an apastron separation of 2.30 AU implies a maximum projected separation on the sky of $\sim 0.03''$. Much of the orbit of this system lies within reach of the diffraction limit of the 85 m baseline of the Keck Interferometer, $0.005''$. Although the K−band magnitude of RX J0529.3+1210, 9.2, is relatively faint for observations with this facility, planned improvements to the system may eventually enable resolved observations of this unusual binary, permitting the determination of individual component masses. The 90 pc distance may also be confirmed by measuring the parallax, which is slightly greater than 10 mas at this distance, and is at the achievable limit of current instrumentation.

5. Summary

Torres et al. (2002) reported the orbital solution for RX J0529.3+1210 based on single-lined spectroscopic data; we have elaborated on this solution using near-IR data to identify the spectrum of the secondary star and determine the mass ratio of the system. The IR data alone presented in a primary vs. secondary velocity plot (Figure 2) indicate a mass ratio of 0.78 ± 0.05. In concert with the visible light data, the full orbital solution yields a more uncertain mass ratio of 0.73 ± 0.23 (Table 3). Other orbital parameters are in good agreement with the results of Torres et al. (2002). This system is the most eccentric pre−main sequence double−lined binary known to date (Figure 4) and thus presents challenges to observation. It is an unlikely site for the formation of circumstellar planets, or of circumbinary planets with orbits within several AU of the stars.

The fact that the secondary component was not identified in visible light suggests a relatively faint and/or red companion. For an estimated primary mass of 0.75 $M_\odot$ the minimum mass of the secondary is 0.40 $M_\odot$. This implies a minimum mass ratio of 0.53, consistent with the value in Table 3. A robust determination of the mass ratio along with the best estimate for the primary star mass will eventually provide an improved estimate for

the secondary mass.

On the basis of the center-of-mass velocity, common proper motion, a lack of near-IR excess, a tentative K-band AO detection of the secondary, lithium equivalent width, and 24 μm *Spitzer* excess evidence for a debris disk, we argue that the RX J0529.3+1210 system is a member of the 32 Ori moving group, recently identified by Mamajek (2007). Assuming a distance of 90 pc, we estimate an age for RX J0529.3+1210 of 15±5 Myr, consistent with that of Mamajek (2007) for 32 Ori.

It is imperative to improve the orbital elements of RX J0529.3+1210 in order to determine a precise mass ratio for the system. In conjunction with future interferometric observations, this will ultimately yield component masses for this system. Given its unusual eccentricity, proximity, young age, and debris disk, such observations are likely to reveal clues to the formation of this unique binary system as well as additional data for the improvement of pre-main sequence models.

The authors are grateful to K. Kilts for conducting the preliminary reduction of these data, to T. Barman and C. Johns-Krull for helpful discussions, and to G. Torres for catching an error in our original manuscript. We thank M. Morales Calderon, D. Barrado y Navascués, and J. Stauffer for sharing the results of their *Spitzer* MIPS data in advance of publication. We appreciate the input of E. Mamajek, on the traits of the 32 Ori moving group, and we are grateful to the anonymous referee for detailed and thoughtful recommendations which improved this paper. This research was funded by NSF grant AST 04-44017 (to LP) and the associated REU supplement, and by NASA Space Grant, through Northern Arizona University, which has provided support for GNM, as well as NSF grant AST 06-07612 (to MS). This work made use of the SIMBAD reference database, the NASA Astrophysics Data System, and the data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. Data presented herein were obtained at the W.M. Keck Observatory from telescope time allocated to the National Aeronautics and Space Administration through the agency's scientific partnership with the California Institute of Technology and the University of California. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. We recognize and acknowledge the significant cultural role that the summit of Mauna Kea plays within the indigenous Hawaiian community and are grateful for the opportunity to conduct observations from this special mountain.

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Table 1. Properties of RX J0529.3+1210

R.A.(J2000) = 05:29:18.8
Dec.(J2000) = +12:09:30
V (mag) = 12.86
J (mag) = 10.05 ± 0.020
H (mag) = 9.40 ± 0.023
K (mag) = 9.19 ± 0.020
SpT[a] = K7-M0
Hα EW[b] (Å) = −2.0
Li EW (Å) = 0.27[a] , 0.35[b]
$v_A \sin i$[a] =18 ± 3 km s^{-1}

[a]Torres et al. (2002)

[b]Magazzù et al. (1997)

Table 2. Summary of Observations and Analysis

UT Date of Observations	Heliocentric Julian Day	v_1 (km s^{-1})	v_2 (km s^{-1})	Phase
2002 Jan 1	2452275.88	24.7	12.3	0.183
2002 Feb 5	2452310.87	26.9	13.9	0.258
2002 Dec 14	2452622.97	19.5	14.9	0.933
2004 Jan 28	2453032.76	15.4	19.7	0.818
2004 Dec 26	2453365.99	2.3	42.3	0.538
2008 Sep 15	2454725.15	15.3	17.9	0.498

Table 3. Orbital Elements and Derived Properties

$P = 461.89 \pm 0.15$ days
$\gamma = 18.38 \pm 0.30$ km s^{-1}
$K_1 = 22.76 \pm 1.59$ km s^{-1}
$K_2 = 31.25 \pm 9.44$ km s^{-1}
$e = 0.88 \pm 0.02$
$\omega = 108 \pm 4$ degrees
$T = 2455187.1 \pm 0.46$ MJD
$M_1 \sin^3 i = 0.454 \pm 0.312$
$M_2 \sin^3 i = 0.330 \pm 0.317$
$q = M_2/M_1 = 0.73 \pm 0.23$
$a_1 \sin i = (67.98 \pm 2.05) \times 10^6$ km
$a_2 \sin i = (93.32 \pm 27.57) \times 10^6$ km

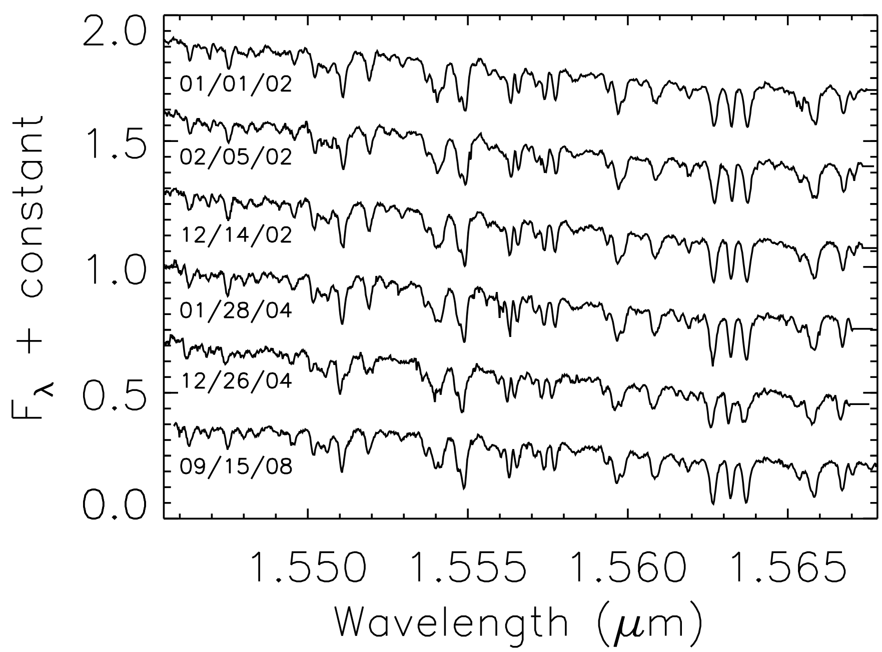

Fig. 1.— Five epochs of spectra for RX J0529.3+1210, with heliocentric corrections applied; UT dates of the observations are indicated. Note the similarity between observations resulting from small radial velocity separations.

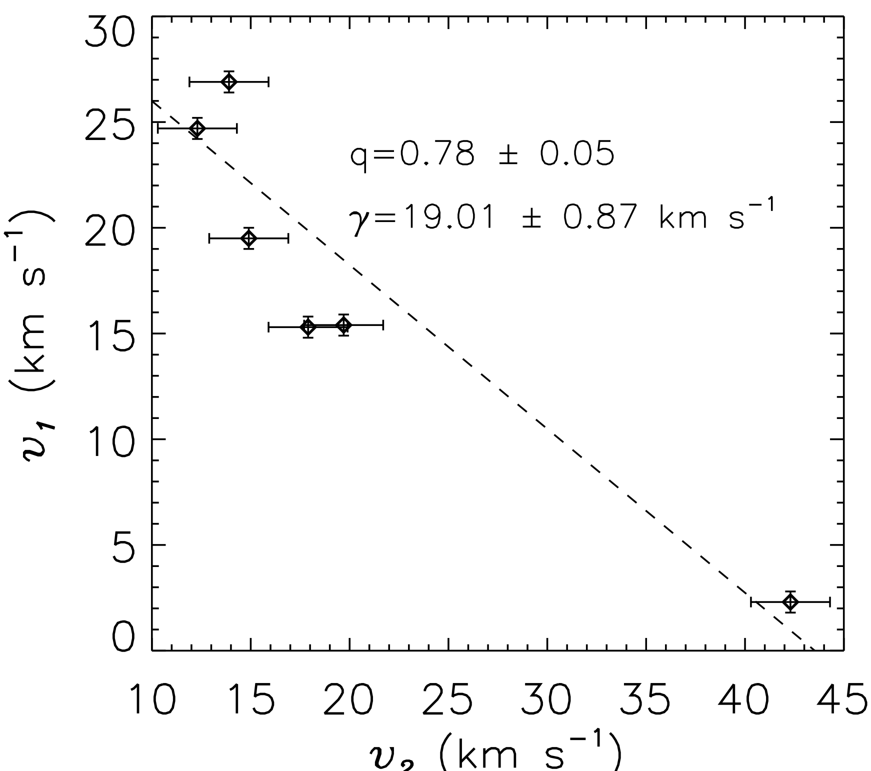

Fig. 2.— Linear fit to the primary versus secondary radial velocities for RX J0529.3+1210 following Wilson (1941). The mass ratio, q, is the negative of the slope of the fit and the center-of-mass velocity is determined by the equation γ=(y-intercept)/(1+q).

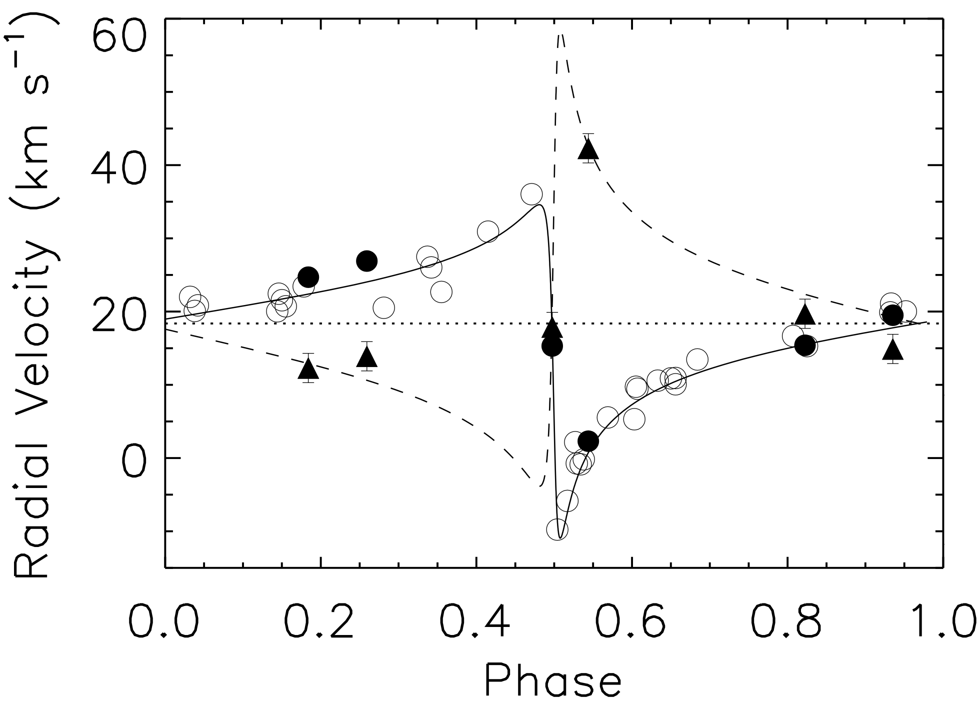

Fig. 3.— Radial velocity as a function of phase for RX J0529.3+1210. The circles represent the primary star data, and the triangles secondary star data. Filled symbols are data from our observations, and hollow symbols are data from Torres et al. (2002). The full orbital solution is represented with a solid line for the primary star and a dashed line for the secondary star. The dotted horizontal line indicates the system's center-of-mass velocity. Uncertainties in the primary star RVs are 0.5 km s^{-1}, smaller than the symbols used. The secondary star RV uncertainties are 2.0 km s^{-1}, as shown.

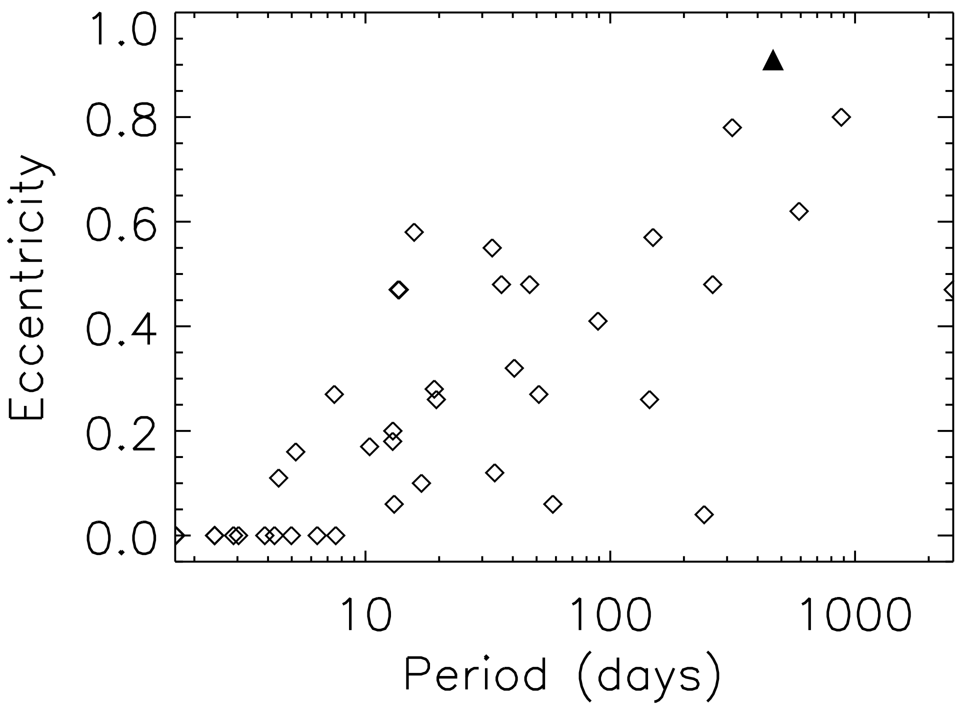

Fig. 4.— Eccentricities of pre-main sequence spectroscopic binaries as a function of period. RX J0529.3+1210 is indicated by the filled triangle. Data from Table 3 of Melo et al. (2001) are indicated by diamonds.